Low Frequency Radar Sounding Through Martian Ionosphere

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Abstract— **In remote radar sounding, it is highly desirable to operate at low frequencies to improve depth of peneteration. For spaceborne sounders, the lowest operating frequency is limited by the effect of the ionosphere due to significant dispersion of the radar waves at near plasma frequency. The ionosphere affects the transmitted waveform through dispersion which demonstrate itself by changing the temporal shape of the wave and additional propagation time delay. The impact on the radar operation is twofold by 1) introducing an unknown delay which makes the surface tracking difficult, and 2)degrading the range compression by changing the chirp shape and duration. In this paper, we present a scheme to compensate for the ionospheric dispersion by taking advantage of the strong specular surface reflection expected at low frequencies. Although the technique which is presented in this paper is generic, all of the discussion in this paper deals with low frequency radar sounding of Mars.**

I. Background

Radar sounders which are typically nadir-looking are valuable remote sensing tools for studying the subsurface of planets. Airborne ice-peneterating radars have been used successfully in detecting sudden changes in the sublayer dielectric constants citeernesto. In 2003, Mars Express spacecraft will carry an experimental radar sounder called Mars Advanced Radar for Subsurface Sounding and Ionosphere *MARSIS* to Martian Orbit to probe the subsurface of Mars [2]. It is desirable to operate the radar at very low frequency since the penetration depth of the sounder is higher at lower frequency. *MARSIS* subsurface sounding operating frequency ranges from 1.3 to 5.5 MHz which is close to the Martian ionosphere's plasma frequency. The proximity of the sounder operating frequency to the plasma frequency of the ionosphere introduces serious complications in the pulse compression process and signal delay tracking. To quantify the effect of the ionosphere on the signal group delay and its phase distorion, a model for the Martian ionosphere needs to be developed. The ionosphere of Mars is not well characterized, especially at the night side, however, it is believed to have a maximum plasma frequency at an altitude of 125-150 km [4] and the maximum nightside plasma frequency is believed to be less than 800 kHz (see Fig. 1). A monochromatic electromagnetic wave propagating through the ionosphere will have a phase shift which can be written as

$$\delta\Phi(f) = 2kh\left(1 - \frac{1}{h}\int_0^h \sqrt{1 - \frac{f_p(z)^2}{f^2}}dz\right) \qquad (1)$$

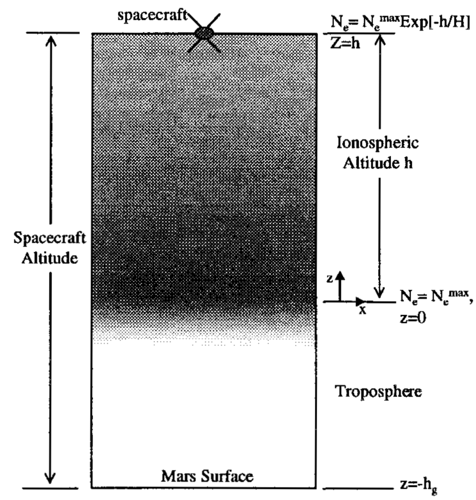

Fig. 1. The Mars ionosphere is assumed to have a maximum plasma frequency at an altitude of 100-150 km and an exponentially decaying structure with a height scale of 30-80 km: z=0 corresponds to the location of maximum electron density (or maximum plasma frequency).

where f is the frequency, $f_p(z)$ is the plasma frequency at height z above the maximum plasma frequency altitude, and h is the spacecraft altitude above the maximum plasma frequency. The plasma frequency $f_p = 8.9\sqrt{N_e}$ depends on the electron density N_e at a given location, where γ is a constant. Since the electron density varies with the altitude, the plasma frequency varies with height and may be modeled as

$$f_p^2(z) = f_p(0)^2 \exp(-z/H). \qquad (2)$$

where H is the $1/e$ height scale for the electron density distribution, $f_p(0)$ is the maximum plasma frequency at height $z = 0$ (from here on $f_p = f_p(0)$), (note that ground is at $z = -h_g$). The result of the integral in Eq. 1 can be written as

$$\delta\Phi(f) \quad = \quad 4kH\left(\sqrt{1 - \frac{f_p^2}{f^2}} - \right.$$

$$\sqrt{1-\frac{f_p^2}{f^2}\exp(-h/H)} - \log(1+\sqrt{1-\frac{f_p^2}{f^2}}) + \log(1+\sqrt{1-\frac{f_p^2}{f^2}\exp(-h/H)}) \quad (3)$$

Since $f_p/f < 1$, the above expression can be expanded around $f_p/f = 0$ yielding

$$\delta\Phi(f) = kH \sum_{m=1}^{M} \frac{1}{M}\frac{f_p^{2m}}{f^{2m}}(\exp(-mh/H)-1) + O((\frac{f_p}{f})^{2M+2}). \quad (4)$$

From the above equation it is clear that for frequencies close to the plasma frequency, higher order terms should be retained to achieve desired accuracy. The change in the group velocity is given by

$$c(f) = \frac{c_0}{\sqrt{1-\frac{f_p^2}{f^2}}}. \quad (5)$$

Consequently, the frequency dependent round-trip delay caused by the ionosphere is given by

$$\tau(f) = \frac{2}{c_0}(h - \int_0^h \frac{1}{\sqrt{1-\frac{f_p(z)^2}{f^2}}}dz) \quad (6)$$

The above integral can be evaluated exactly, by assuming the same exponential electron density profile, and can be written as

$$\tau(f) = \frac{4H}{c_0}\frac{\log(1+\sqrt{1-\frac{f_p(z)^2}{f^2}\exp(-h/H)})}{\log(1+\sqrt{1-\frac{f_p(z)^2}{f^2}})} \quad (7)$$

The above equation for the delay can be expanded around $f_p/f = 0$ and the resulting equation may be written as

$$\tau(f) \approx H((1-\exp(-h/H))(\frac{f_p}{f})^2 + \frac{3}{8}(1-\exp(-2h/H))(\frac{f_p}{f})^4 \frac{5}{24}(1-\exp(-3h/H))(\frac{f_p}{f})^6)) + O((\frac{f_p}{f})^8 \quad (8)$$

II. IONOSPHERIC EFFECT ON THE SUBSURFACE SOUNDING

The subsurface sounding is carried out on the night-side of the Mars for which there is little information on the maximum plasma frequency and electron density height scale. The plasma frequency is expected to be lower than 800 kHz (maybe as low as 80 kHz). This large uncertainty in the plasma frequency results in a wide range of possible delays in the returned signal. Other parameters that affect the signal delay and phase distortion are ionosphere's electron density profile defined by the height scale parameter H (approximately 30-70 km) and propagation distance in the ionosphere h which is a function of spacecraft altitude and maximum plasma frequency altitude. The effect due to the variation of these parameters are not as significant as the maximum plasma frequency. In order to demonstrate the impact of the ionosphere on the chirp signal, the received signal was calculated for all four bands using the nominal value of the ionosphere parameters which are, $H = 65$ km, $h_p = 125$ km, $h_s = 300$ km, and maximum plasma frequency $f_p = 800$ kHz. Based on these parameters, it is possible to calculate the total delay in reception and phase distortion of the signal. The longest delay corresponds to the lowest frequency of 1.3 MHz and the highest plasma frequency of 800 kHz and is equal to 91 μsec. The delay for the highest frequency of the same band which is 2.3 MHz is 55 μsec. There is approximately a 36 μsec difference in delay between edges of the band. For a short 30 μsec up-chirp, such a delay will cause a contraction in the chirp length. As it will be discussed later, this effect is similar to a chirp compression procedure. Figures 2, and 3 show the received chirp after round-trip propagation in the ionosphere for bands 1 and 4 respectively. These figures clearly demonstrate that the signals in the lowest band is significantly distorted.

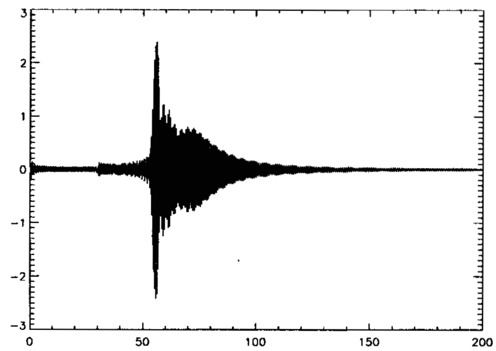

Fig. 2. The received chirp for band 1 before down-conversion: The original chirp length of 30 μs is extended to about 65 μs due to severe dispersion on the lower part of the band, also there is a minimum of approximately 55 μs delay.

III. SIGNAL COMPRESSION USING THE SURFACE REFLECTED SIGNAL

In order to compress a chirp signal which is distorted by the ionosphere, the reference chirp needs to modified to account for the ionospheric phase distortion. In general, this would require the explicit knowledge of the spatial electron density distribution function of the ionosphere. This is a very strict requirement which is very difficult to satisfy for real time com-

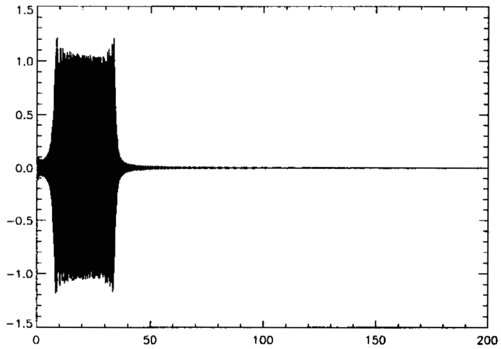

Fig. 3. The received chirp for band 4 before down-conversion: The original chirp length of 30 μs is reduced to about 27 μs due to dispersion, also there is a 7 μs delay .

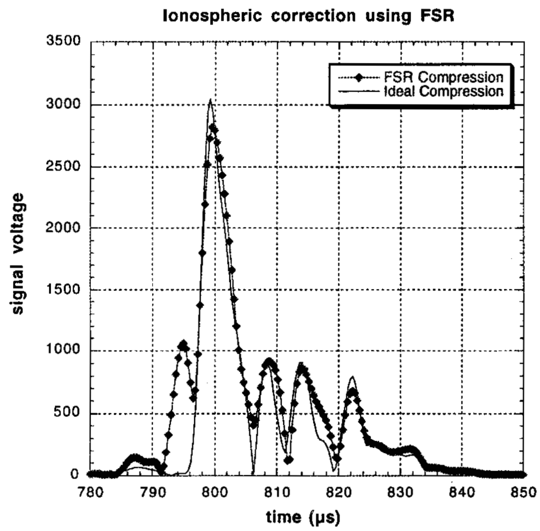

Fig. 4. A comparison of the compression performance for a signal transmited through the ionosphere and compressed with both an ideal reference chirp (complete ionosphere knowledge) and the gated front surface reflection

pression operation in a dynamic ionosphere. Fortunately, when there is a smooth interface which gives rise to a strong specular reflection, the ionospheric information is implicitly included in the front surface reflection signal [3]. In this case, the early portion of the signal is time-gated with a gate whose length is equal to the expected specularly reflected signal. This method performs best when there is little surface clutter signal which is expected to be true for Mars at 1-5 MHz frequency band. The performance is remarkably high even in the high clutter situations. An example of such a compression result in the presence of clutter is shown in Fig. 4. The figure shows the compression result with both an ideal reference chirp and gated front surface reflection for a surface with roughness in the 80 percentile of roughest Martian surfaces. As shown in Fig. 4, the compression quality is very good, however, there are artifacts due to the presence of the clutter in the reference chirp. Since the clutter signal generally arrives later than the specular return (as is the case here), the artifacts due to the correlation of the reference function in the presence of the clutter appears before the main peak corresponding to the front surface signal. This is a helpful property and can be exploited as an indicator of the reference function quality. The signal example shown in this case was simulated using the signal model

$$s(\omega) = \frac{1}{\jmath\lambda} \int \int \frac{\exp[2k(R - h(x,y)\cos(\theta)}{R^2} \cos\theta dxdy, \quad (9)$$

where λ is the wavelength, $k = 2\pi/\lambda$ is the wavenumber, R is the distance to the scatterer, and $h(x, y)$ is the height above the reference plane. For the above example, the height h(x,y) was obtained from a Digital Elevation Map (DEM) of an area that resembles the roughest 80 percentile on Mars. The time domain signal is reconstructed from signal frequency samples spaced at 2.5 kHz. The ionospheric distortion is included in the simulation by adding the ionospheric phase distorion to the signal spectrum phase.

IV. SUMMARY

A model for the ionospheric dispersion of Mars was developed and its impact as a dispersive waveguide on the electromagnetic wave propagation was studied. The derived models as well as numerical simulation of a chirp signal propagating through the ionosphere indicates significant distortion for all bands. Further, the lower two bands are dispersed in a nonlinear fashion. This means a single slope parameter adjustment of the reference chirp will not adequately compensate for the ionospheric dispersion. Naturally, all of these conclusions are strongly dependent on the maximum plasma frequency of the Martian ionosphere.

V. ACKNOWLEDGMENT

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